

MASS TRANSFER AND THE PERIOD DECREASE IN RX J0806.3+1527

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ABSTRACT

We examine the nature of RX J0806.3+1527 and show that it is possible to reconcile the observed period decrease and X-ray luminosity with the transfer of mass between two white dwarfs provided that: either the system is (i) still in the early and short-lived ($\lesssim 100$ yr) stages of mass transfer due to atmospheric Roche-lobe overflow, or (ii) in a standard, long-term, quasi-stationary mass-transfer phase that is significantly ($\sim 90\%$) non-conservative and the conversion of accretion energy to X-rays is quite inefficient. In either of the two cases and for a wide range of physical parameters, we find that orbital angular momentum is lost from the system at a rate that is a factor of a few ($\lesssim 4$) higher than the rate associated with the emission of gravitational waves. Although the physical origin of this extra angular momentum loss is not clear at present, it should be taken into account in the consideration of RX J0806.3+1527 as a verification Galactic source for LISA.

Subject headings: Stars: Binaries: Close, Stars: White Dwarfs, Gravitational Waves

1. INTRODUCTION

In recent years, much attention has been devoted to the nature of the X-ray source RX J0806.3+1527. The source was discovered by ROSAT in 1990 (Beuermann et al. 1999) and found to be variable with a period of ~ 321 s by Israel et al. (1999). The latter authors tentatively ascribed the periodicity to the rotation of a white dwarf in an intermediate polar type cataclysmic variable (see also Beuermann et al. 1999; Burwitz & Reinsch 2001; Norton, Haswell, & Wynn 2004). The absence of a second period (corresponding to the orbital motion) and the presence of He emission lines in an optical follow-up, however, lead Israel et al. (2002) to reclassify the system as an AM CVn type double degenerate. In this picture, the ~ 321 s periodicity reflects the orbital motion, making RX J0806.3+1527 the tightest known binary to date (see also Burwitz & Reinsch 2001; Ramsay, Hakala, & Cropper 2002) and an excellent verification source for the gravitational-wave space mission LISA planned by NASA and ESA.

More recent observations revealed two possibly major problems for the AM CVn model: (i) Israel et al. (2003), assuming a distance of 500 pc, derived a *low* average X-ray luminosity of $\simeq 5 \times 10^{32}$ erg s⁻¹, and (ii) Hakala et al. (2003) and Strohmayer (2003) found the observed period to be *decreasing* with time at a rate of $\simeq 10^{-11}$ s s⁻¹ (see also Israel et al. 2004; Strohmayer 2005). The X-ray luminosity poses a problem because it is significantly below the luminosity expected from mass accretion in compact double white dwarfs, while the period decrease poses a problem because mass transfer in AM CVns is expected to expand the orbit rather than shrink it. A third possible model was therefore proposed to be the unipolar inductor model developed by Wu et al. (2002). In this model the X-ray flux is generated by electric currents between two close but detached white dwarfs. However, shortcomings of this model have recently been pointed out by Barros et al. (2005) and Marsh & Nelemans (2005). The question on the nature of RX J0806.3+1527 therefore still remains open.

In this *Letter*, we revisit the AM CVn model for RX J0806.3+1527 and investigate under which conditions the assumption of mass transfer (MT) between two white dwarfs can comfortably explain all the currently available observa-

tional constraints. Our motivation stems from both trying to understand the origin of the X-ray emission and the measured period decrease and to examine the physical properties of this binary and its role as a verification source for LISA.

2. THE MASS AND RADIUS OF THE DONOR STAR

We assume RX J0806.3+1527 to be an AM CVn type double degenerate with an orbital period $P_{\text{orb}} = 5.4$ min (~ 321 s). We denote the masses of the two white dwarfs (WD) by M_1 and M_2 , and assume $M_1 > M_2$ so that the primary corresponds to the mass accretor and the secondary to the mass donor. Since the evolutionary channels leading to the formation of AM CVns involve multiple MT phases (e.g., Han 1998; Nelemans et al. 2001a), the orbit can be safely assumed circular.

The assumptions that the observed periodicity of 5.4 min corresponds to the orbital period and that the secondary fills its critical Roche lobe can be used to constrain the mass M_2 and radius R_2 of the donor. For this purpose, we first determine the radius of the secondary as a function of its mass by means of the mass-radius relation for zero-temperature WDs (Nauenberg 1972):

$$R_2 = 0.01125 R_{\odot} \left[\left(\frac{M_2}{M_{\text{ch}}} \right)^{-2/3} - \left(\frac{M_2}{M_{\text{ch}}} \right)^{2/3} \right]^{1/2}, \quad (1)$$

where M_{ch} is the Chandrasekhar mass (see also Han & Webbink 1999). The resulting radii are shown in Fig. 1 (solid line). Next, we consider the mass-radius relations for finite temperature helium WDs with masses from 0.1 to 0.4 M_{\odot} derived by Hansen & Phinney (1998). Radii for effective temperatures $T_2 = 5 \times 10^3$ and 10^4 K, and hydrogen envelopes of $M_{\text{H}} = 10^{-6}$ and $3 \times 10^{-4} M_{\odot}$ are shown in Fig. 1 (long-dashed lines). They are systematically larger than radii for zero-temperature WDs, with the largest differences occurring at the lowest masses.

Under the assumption that the secondary is not significantly out of thermal equilibrium, its radius is approximately equal to the volume-equivalent radius R_{L2} of its critical Roche lobe (see Eggleton 1983). The variations of the latter as a function of M_2 are shown in Fig. 1 (short-dashed lines) for $P_{\text{orb}} = 5.4$ min and $M_1 = 0.2, 0.6, 1.0, 1.4 M_{\odot}$. It follows that, for zero-temperature WD models, $R_2 = R_{\text{L2}}$ for $M_2 = 0.13 M_{\odot}$ and $R_2 = 0.024 R_{\odot}$ (cf. Israel et al. 2002). Finite-temperature mass-radius models yield larger donor masses and radii. For

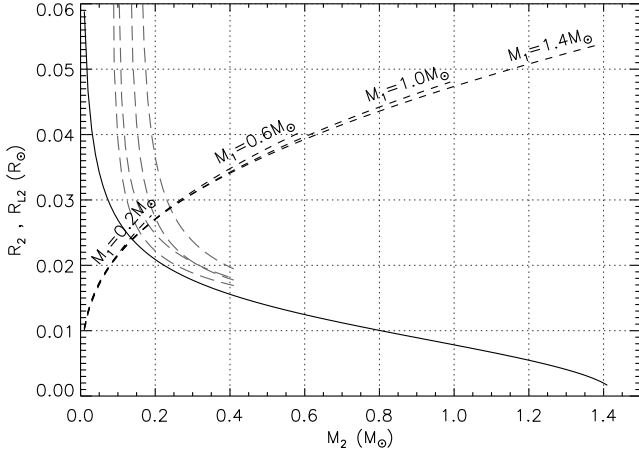


FIG. 1.— Mass-radius relations for zero-temperature (solid line) and finite temperature (long-dashed lines) WD models. From left to right, the finite temperature models correspond to $(M_H/M_\odot, T_2/K) = (10^{-6}, 5 \times 10^3), (3 \times 10^{-4}, 5 \times 10^3), (10^{-6}, 10^4), (3 \times 10^{-4}, 10^4)$. The donor Roche-lobe radii for $P_{\text{orb}} = 5.4$ min, $M_1 = 0.2, 0.6, 1.0, 1.4 M_\odot$, and $M_2 < M_1$ are also shown (short-dashed lines).

$T_2 = 10^4$ K and $M_H = 3 \times 10^{-6} M_\odot$, e.g., $M_2 = 0.24 M_\odot$ and $R_2 = 0.029 R_\odot$.

3. THE MASS-TRANSFER RATE AND X-RAY LUMINOSITY

In AM CVn binaries, the observed X-ray luminosity is generated by mass accretion onto the primary. Ramsay et al. (2005) have shown that a large fraction of the accretion luminosity in AM CVns is radiated in the UV rather than in X-rays. In particular, they estimated the ratio of the X-ray luminosity to the UV luminosity to be $\sim 1/1000$ for AM CVn and $\sim 1/3$ for GP Com. In order to accommodate this, we set $L_X = \alpha L_{\text{acc}}$, where L_X and L_{acc} are the X-ray and total accretion luminosity, respectively, and $0 \leq \alpha \leq 1$. We conservatively set $\alpha = 0.1$ and we note that α can very well be lower by 1-2 orders of magnitude. The linear dependence of L_X on α allows for an easy rescaling of our results for different values of α .

The accretion luminosity due to MT is given by

$$L_{\text{acc}} = -\beta \dot{M}_2 (\Phi_{L1} - \Phi_{R1}), \quad (2)$$

where β is the fraction of the transferred mass accreted by the primary, and Φ_{L1} and Φ_{R1} are the Roche potential values at the inner Lagrangian point and at the surface of the accretor, respectively (see Han & Webbink 1999 for details, but note the reverse definition of M_1 and M_2). To determine Φ_{R1} , we model the accretor as a zero-temperature white dwarf, noting that finite temperatures lead to an increase in the radius and thus a decrease in the absolute value of Φ_{R1} and L_{acc} .

3.1. Quasi-Stationary Mass Transfer

In order to estimate the accretion rate and X-ray luminosity, we need to determine \dot{M}_2 from the donor. We assume that MT turns on instantaneously when $R_2 = R_{L2}$ and that \dot{M}_2 is given by the quasi-stationary rate

$$\dot{M}_2 = -\frac{M_2}{\zeta_{s2} - \zeta_{L2}} \left(\frac{\dot{R}_2}{R_2} - 2 \frac{\dot{J}_{\text{orb}}}{J_{\text{orb}}} \right). \quad (3)$$

Here J_{orb} is the orbital angular momentum, \dot{R}_2 and \dot{J}_{orb} correspond to time derivatives of R_2 and J_{orb} at constant mass, $\zeta_{s2} = (\ln R_2 / \ln M_2)_s$ is the donor's adiabatic radius-mass exponent, and $\zeta_{L2} = (\ln R_{L2} / \ln M_2)$ (e.g. Rappaport, Joss, &

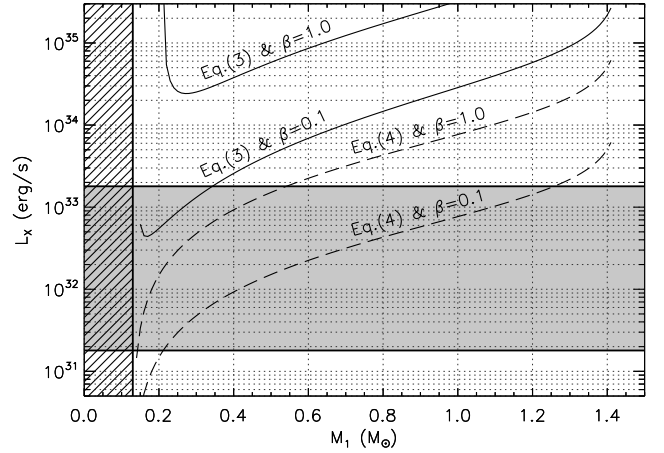


FIG. 2.— Variations of L_X as a function of M_1 , for zero-temperature WDs, $M_2 = 0.13 M_\odot$, $\alpha = 0.1$, and $\beta = 0.1$ or 1. Solid lines correspond to the quasi-stationary MT rate with $\dot{J}_{\text{orb}} = \dot{J}_{\text{GR}}$ [Eq. (3)]; dashed lines to the turn-on rate [Eq. (4)]. The grey horizontal band indicates the observationally inferred L_X for distances of 100–1000 pc. Accretors with $M_1 < 0.13 M_\odot$ (hatched area) are excluded because of the $M_1 > M_2$ assumption.

Webbink 1982; Ritter 1988; Han & Webbink 1999). Expressions for ζ_{s2} and ζ_{L2} appropriate for WDs are given by Han & Webbink (1999)¹. For our purpose, we neglect changes in the stellar radius related to the cooling of the white dwarf at constant mass, and assume the orbital evolution in the absence of MT to be driven entirely by orbital angular momentum losses due to gravitational radiation (GR). In Eq. (3), we then have $\dot{R}_2 = 0$ and $\dot{J}_{\text{orb}} = \dot{J}_{\text{GR}}$.

For zero-temperature WDs (i.e. $M_2 = 0.13 M_\odot$), we calculate $\dot{M}_2 \sim 10^{-7} - 10^{-5} M_\odot \text{ yr}^{-1}$ for conservative MT ($\beta = 1$), and $10^{-7} - 10^{-6} M_\odot \text{ yr}^{-1}$ for non-conservative MT ($\beta = 0.1$). The associated X-ray luminosities are shown in Fig. 2 as functions of M_1 (solid lines). For $\beta = 1$, L_X is well outside the grey horizontal band indicating the observational constraints on L_X for distances between 100 and 1000 pc (Israel et al. 2002, Marsh & Nelemans 2005). For $\beta = 0.1$, the calculated L_X is consistent with the observed one if $0.13 \lesssim M_1/M_\odot \lesssim 0.35$, a very narrow range of accretor masses². For a given value of β , finite temperature WDs give systematically higher MT rates and thus higher L_X values.

We conclude that the quasi-stationary MT rate [Eq. (3)] yields L_X values that are only marginally compatible with the observed range, *unless* $\alpha \simeq 1/1000$ (as for AM CVn) and $\beta \simeq 0.1$. However, it should be noted that the quasi-stationary rate is only representative of the long-term average MT rate. Marsh & Nelemans (2005) estimated that deviations from the quasi-stationary rate can take place on time scales of ~ 100 yrs, suggesting that below-average MT rates could be sustained for time spans sufficiently longer than the 15 years since the discovery of the source. The mechanism responsi-

¹ The ζ_{s2} expression derived by Han & Webbink (1999) is valid only for zero-temperature WDs [M_2 - R_2 relation as in Eq. (1)]. In our finite-temperature WD calculations we therefore use a generalization of ζ_{s2} based on the M_2 - R_2 relations of Hansen & Phinney (1998). The adopted expression for ζ_{L2} is derived under the assumption that any mass lost from the system carries away the specific orbital angular momentum of the accretor.

² Equation (2) is often approximated by $L_{\text{acc}} = -\beta G M_1 \dot{M}_2 / R_1$. However, as noted by Han & Webbink (1999), this is inappropriate for compact double WDs in which the donor is located deep within the potential well of the accretor. For the system parameters considered here, the use of the approximation yields L_X values up to a factor of ~ 5 larger than those shown in Fig. 2.

ble for driving the MT rate away from its equilibrium value remains unclear, but, as noted by Marsh & Nelemans (2005), a comforting list of candidates exist, although their applicability to double WDs has yet to be investigated.

3.2. Atmospheric Roche-lobe Overflow

Alternatively, the MT rate in RX J0806.3+1527 could also be below its long-term average if the system started MT only recently, and therefore is in a stage of atmospheric Roche-lobe overflow (RLO) and has yet to evolve towards the quasi-stationary state. A modified rate applicable to turn-on MT was derived by Ritter (1988) who pointed out the role of the atmospheric properties of the donor star during the turn-on phases (see also D’Antona, Mazzitelli, & Ritter 1989; Kolb & Ritter 1990). We therefore reconsider the L_X derivation under the assumption that MT started only recently.

Following Ritter (1988), we determine

$$\dot{M}_2 = -\frac{2\pi}{\sqrt{e}} \left(\frac{\mathcal{R} T_2}{\mu_2} \right)^{3/2} \frac{R_{L2}^3}{G M_2} \rho_2 F_2(q) \exp\left(-\frac{R_2 - R_{L2}}{H_{P2}}\right), \quad (4)$$

with an associated exponential turn-on time scale

$$\tau_{\dot{M}_2} = -\frac{1}{2} \frac{H_{P2}}{R_2} \frac{J_{\text{orb}}}{\dot{J}_{\text{orb}}}. \quad (5)$$

Here G is the Newtonian constant of gravitation, \mathcal{R} the universal gas constant, T_2 the effective temperature, ρ_2 the photospheric mass density, μ_2 the photospheric mean molecular weight, and H_{P2} the photospheric pressure scale height. Furthermore, $F_2(q)$ is a function of the mass ratio $q = M_1/M_2$ which, for $0.5 \lesssim q \lesssim 10$, can be approximated as $F_2(q) = 1.23 + 0.5 \log q$.

From Eq. (4), it is clear that, although convenient for the derivation of mass-radius relations, the zero-temperature approximation is not suitable when considering the turn-on MT rate in semi-detached double WDs. Instead we determine \dot{M}_2 for a WD donor with a finite but low effective temperature $T_2 = 2500$ K. We set the mean molecular weight $\mu_2 = 4$, as appropriate for a non-ionized helium-rich gas, and adopt the equation of state of an ideal gas to determine the mass density ρ_2 from the pressure P_2 and temperature T_2 . From the temperature-pressure stratifications for cool white dwarfs derived by Saumon & Jacobson (1995) and Rohrmann (2001), it then follows that $P_2 \simeq 10^9$ dyn cm $^{-2}$ and $\rho_2 \simeq 2 \times 10^{-2}$ g cm $^{-3}$. The corresponding pressure scale height for $M_2 = 0.13 M_\odot$ and $R_2 = 0.024 R_\odot$ is $H_{P2} \simeq 5 \times 10^{-6} R_2$. Setting $R_2 = R_{L2}$ then yields MT rates $\dot{M}_2 \simeq 5 \times 10^{-9} M_\odot \text{ yr}^{-1}$ and exponential turn-on time scales $\tau_{\dot{M}_2} \simeq 2\text{--}12$ yrs. The corresponding X-ray luminosities are shown in Fig. 2 (dashed lines). They are considerably lower than those obtained using the quasi-stationary MT rate and are consistent with the observed L_X for a wide range of M_1 values, especially for $\beta \simeq 0.1$. We note however that if $\alpha \sim 1/1000$, the $\beta \sim 1$ case is more favorable.

The derivation for WDs of 5×10^3 K and 10^4 K yields $\dot{M}_2 \simeq 2 \times 10^{-10}$ and $\simeq 10^{-12} M_\odot \text{ yr}^{-1}$, and turn-on time scales of $\simeq 5\text{--}15$ and $\simeq 5\text{--}20$ yrs, respectively. The associated L_X are therefore even lower than those shown in Fig. 2.

4. THE ORBITAL ANGULAR MOMENTUM LOSS RATE

The AM CVn model for RX J0806.3+1527 implies that the orbital period should be increasing in time, unless additional orbital angular momentum loss mechanisms besides GR are operating in the system; or if MT started so recently that

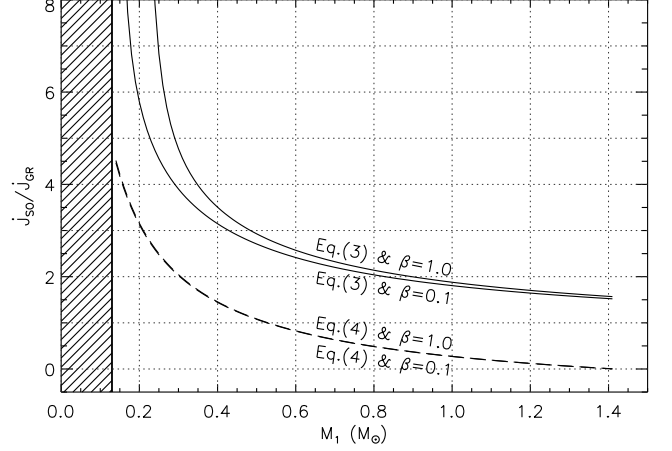


FIG. 3.— The orbital angular momentum loss rate due to spin-orbit coupling required for the AM CVn model to be compatible with the observed period decrease in RX J0806.3+1527. Solid lines correspond to the quasi-stationary MT rate for zero-temperature WDs [Eq. (3)]; dashed lines to the turn-on rate for $T_2 = 2500$ K WDs [Eq. (4)]. In the latter case, the curves associated with $\beta = 0.1$ and 1 are almost indistinguishable because of the small contribution of the \dot{M}_2 terms in Eqs. (6)–(8). Both the zero-temperature and $T_2 = 2500$ K calculations are based on a donor mass of $0.13 M_\odot$. The hatched region is excluded for the same reason as in Fig. 2.

the accompanying orbital expansion has yet to overtake the orbital contraction driven by GR. Exploration of the latter possibility requires detailed MT calculations using realistic WD models, which is beyond the scope of this investigation. Instead, we focus on the additional orbital angular momentum losses required to reconcile the predicted orbital evolution with the measured period decrease of $3.6 \times 10^{-11} \text{ s s}^{-1}$ (Strohmayer 2005). We tentatively ascribe the additional orbital angular momentum losses to spin-orbital coupling through tides and/or magnetic fields, although our analysis is generally valid for other mechanisms as well.

From the definition of J_{orb} and Kepler’s third law, it follows that

$$\frac{\dot{J}_{\text{orb}}}{J_{\text{orb}}} = \frac{1}{3} \frac{\dot{P}_{\text{orb}}}{P_{\text{orb}}} + \left[\frac{1}{M_2} - \frac{\beta}{M_1} - \frac{1-\beta}{3(M_1+M_2)} \right] \dot{M}_2. \quad (6)$$

Writing \dot{J}_{orb} as the sum of the contributions from gravitational radiation (GR), spin-orbit coupling (SO), and systemic mass loss due to non-conservative mass transfer (MT), on the other hand, yields

$$\dot{J}_{\text{orb}} = \dot{J}_{\text{GR}} + \dot{J}_{\text{SO}} + \dot{J}_{\text{MT}}. \quad (7)$$

The first two terms in Eq. (7) operate in both detached and semi-detached double WDs. The third term becomes active only after the onset of MT. We model this term assuming that any systemic mass loss carries away the specific orbital angular momentum of the accretor, i.e.

$$\dot{J}_{\text{MT}} = (1-\beta) \frac{M_2}{M_1} \frac{J_{\text{orb}}}{M_1+M_2} \dot{M}_2. \quad (8)$$

Substitution of Eqs. (6) and (8) into Eq. (7), and use of the well known expression for \dot{J}_{GR} (e.g Landau & Lifshitz 1962) and the observed period and rate of period decrease yields the \dot{J}_{SO} values required for consistency with observations. For zero-temperature WDs ($M_2 = 0.13 M_\odot$), \dot{J}_{SO} is shown in Fig. 3 in units of \dot{J}_{GR} . In the case of the quasi-stationary MT rate [Eq. (3)], $\dot{J}_{\text{SO}} \simeq 1.5 \dot{J}_{\text{GR}}$ for $M_1 \simeq 1.4 M_\odot$,

and $\dot{J}_{\text{SO}} \gtrsim 3.5 \dot{J}_{\text{GR}}$ for $M_1 \lesssim 0.35 M_\odot$ (the M_1 range where the calculated L_X for $\alpha = 0.1$ and $\beta = 0.1$ is consistent with the observed one). For 5×10^3 K and 10^4 K WDs, \dot{J}_{SO} is even larger. On the other hand, in the case of the turn-on MT rate [Eq. (4)], $\dot{J}_{\text{SO}} \lesssim 4.5 \dot{J}_{\text{GR}}$ over the entire M_1 range, and \dot{J}_{SO} is negligible ($\simeq 10^{-3} \dot{J}_{\text{GR}}$) for $M_1 \simeq 1.4 M_\odot$. This also applies to finite WD temperatures because of the low MT rates during the onset of RLO.

5. DISCUSSION AND CONCLUSIONS

We have revisited the AM CVn model for RX J0806.3+1527 and confronted its theoretical predictions with the observational constraints. For an orbital period of 5.4 min and a donor temperature of less than 10^4 K, RLO from the secondary occurs for $M_2 \simeq 0.13\text{--}0.24 M_\odot$ and $R_2 \simeq 0.024\text{--}0.029 R_\odot$. Under the assumptions that 10% of the transferred mass is accreted by the companion, and that 10% of accretion luminosity is radiated in X-rays, the X-ray luminosity due to accretion is found to be comfortably consistent with the observed X-ray luminosity within the distance uncertainties ($d \lesssim 1$ kpc).

We have examined both long-term quasi-stationary and short-term atmospheric MT with exponential growth. We found that the predicted L_X and \dot{J}_{orb} are more comfortably reconciled with the observations in the latter of the two cases. The lower MT rates for atmospheric RLO yield lower accretion luminosities, which significantly alleviates the constraints on the fraction of the mass accreted by the companion and the fraction of the accretion luminosity emitted in X-rays. The predicted orbital evolution is compatible with the measured period decrease, if orbital angular momentum losses other than just GR (e.g. due to spin-orbit coupling) generally play a non-negligible role. We find that, in the case of quasi-stationary MT, an extra loss rate of at least a factor of $\simeq 1.5$ times the GR rate is required. On the other hand, in the case of atmospheric MT, this factor is smaller than 4.5 over the entire M_1 range and vanishes altogether for $M_1 \gtrsim 1.2 M_\odot$. The drawback of the atmospheric RLO hypothesis is that MT must have started only very recently (within $\simeq 5 \times \tau_{M_2}$, i.e., at most ~ 100 yr).

The standard hypothesis of quasi-stationary MT, however, can also become consistent with observations if MT is significantly non-conservative and the fraction of the accretion luminosity emitted in X-rays (instead of UV) is as low ($\simeq 1/1000$) as estimated by Ramsay et al. (2005) for AM CVn. The drawback of this hypothesis is that the required additional orbital angular momentum losses are about 1.5–4 times the GR loss

rate (for $M_1 \gtrsim 0.3 M_\odot$). Without a detailed study of spin-orbit coupling through tides and/or magnetic fields it is not obvious whether such high loss rates are sustainable.

Besides spin-orbit coupling, the rate of orbital angular momentum loss can also be increased if matter leaving the system is assumed to carry away the specific orbital angular momentum of the donor rather than that of the accretor. In addition, if RX J0806.3+1527 is a direct impact accretor, the absence of an accretion disk provides yet another orbital angular momentum sink since no angular momentum from the accreted material can be directly fed back into the orbit (Marsh, Nelemans, & Steeghs 2004). We also note that in the case of quasi-stationary MT, these extra orbital angular momentum losses tend to increase \dot{M}_2 and L_X [see Eqs. (2)–(3)]. For $M_1 \gtrsim 0.3 M_\odot$ the increase is smaller though than the orders of magnitude uncertainty in the fraction of the accretion luminosity emitted in X-rays.

We conclude that, in view of the uncertainties in the WD temperatures, the MT mechanism, the fraction of the accretion luminosity radiated in X-rays, and the acting orbital angular momentum loss mechanisms, the observed X-ray luminosity and rate of period decrease cannot be used to exclude that RX J0806.3+1527 is an AM CVn type double degenerate. The standard association of accretion and X-ray emission does not at all appear inconsistent with the current observations and hypotheses about the origin of the X-rays being unrelated to accretion are not necessary.

The present study reveals the possibility of additional angular momentum loss rates due to spin-orbit coupling in double WDs and clearly indicates that the use of these interacting binaries in LISA detection and data analysis may not be as straightforward as previously thought.

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